U. S. NAVY MV TYPE OF HYDROPHONE AS AN AID AND SAFEGUARD TO NAVIGATION.

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Summary.

The experimental work in connection with hydrophone development, which the United States Navy has carried out during the past year, has demonstrated that the MV type of hydrophone can effectively aid and safeguard navigation in the following ways:

1. By hearing and locating a moving propeller-driven vessel at ranges varying from 2 to 10 miles, depending upon the amount of noise which the vessel makes and providing the depth is within 100 fathoms.
2. By accurately determining the direction of submarine sound signals, located at fixed points along the coast and at harbor entrances, at various ranges up to 30 miles, depending upon the amount of local or water noises encountered.
3. By giving a continuous sounding record while underway at any speed for depths less than about three times the length of the vessel.
4. By hearing, locating, and giving the course of any vessel equipped with a suitable submarine sound signal at ranges up to 30 miles.
5. By affording a means of exchanging code messages between vessels equipped with the proper apparatus up to ranges of 20 miles in water of any depth, thus giving an auxiliary to the radio.

The results of the various tests that have thus far been carried out indicate that this type of hydrophone will prove capable of further aiding and safeguarding navigation in the following ways:

6. By giving a fairly accurate, intermittent sounding record while the vessel is under way in water of any depth, providing the vessel is equipped with a suitable submarine sound-signaling device.
7. By giving the distance of a submarine sound signal.
8. By locating icebergs, derelicts, or precipitous coasts at ranges sufficient for avoiding collisions.

Hydrophones Developed by the U. S. Navy.[1]

The hydrophones developed by the United States Navy differ from all others in that they employ a multiplicity of non-resonant, underwater sound receivers, having sufficient time lag (compensation) introduced into the path of energy traverse between each receiver and the ear to bring the energy from all the receivers to the ears in phase.

The receivers are placed at equal intervals along a horizontal line. The dimensions of the group of receivers (length of line) is sufficiently great to cause an appreciable change in phase relations between the responses from the several receivers whenever the direction of the sound-source relative to the line of receivers is changed.

Navy hydrophones employing multiple receivers are of two classes, namely; those employing fixed compensation wherein the line of receivers can be rotated about a vertical axis, and those employing variable compensation wherein the receivers are fixed in position. The present paper deals with the latter class of hydrophones, the so-called "MV Types."

Why the Navy Tested the Ability of the MV Hydrophone to Safeguard Navigation.

At the time of the Armistice the MV type of hydrophone, although not completely developed, was proving to be superior to other types of on-board installations. Accordingly when the prob-

[1] For a more complete description of various types of hydrophones, see paper "Detection of Submarines," by Dr. H. C. Hayes, Proceedings of American Philosophical Society, Vol. XIX., No. 1, 1920.

lem of transporting our troops back again arose it was suggested that this device, if installed on transports, might prove to be of value in safeguarding the lives of these men during fog or other conditions of low visibility. This suggestion was strongly backed by Rear Admiral B. C. Decker, U.S.N., then Senior Member of the Special Board on Anti-Submarine Devices, and by Captain J. R. Defrees, U.S.N., Secretary of the Board, and led to the equipping of the U. S. S. *Von Steuben* with an electrical MV hydrophone for the purpose of ascertaining whether or not such a device could effectively serve as an aid and safeguard to navigation.

Experimental Results Obtained on the U. S. S. Von Steuben.

The writer was fortunate in having charge of the hydrophone installation on the *Von Steuben* during the first trip from Hoboken to Brest and return, a trip which in his opinion will come to be regarded as epoch-making in the annals of navigation.

The *Von Steuben* proceeded at one third speed while leaving New York harbor. During this period neighboring tugboats and ferries were readily located by determining the direction of their propeller sounds. Arrangements had been made to have the lightships along the approach to New York harbor sound their submarine bells and the signals from all these lightships (Ambrose, Fire Island, Cardinal, and Finch) were picked up in turn by the hydrophone and the vessels located before they could be seen. Several times signals from two or three of the lightships could be heard and located at the same time and the position of the *Von Steuben* determined by cross-bearings.

It was not expected that the bell signals from the Nantucket lightship could be heard as the course of the *Von Steuben* lay well to the southward of this vessel and the listeners turned in for the night. The writer's assistant, Ensign D. W. McElroy, U.S.N.R.F., having awakened at about 1 A.M., decided to listen on the hydrophone and heard the bell signals from this vessel coming in clearly and distinctly. The *Von Steuben* at this time was steaming at full speed. The bell was followed for two hours, during which time the light on the Nantucket lightship was not sighted. The range and

position of this vessel relative to the *Von Steuben* were determined later by triangulation, using the distance covered during the two hours as a base-line. These results checked closely with determinations made by dead reckoning and showed that the lightship was never approached closer than 32 nautical miles and that the greatest range at which the bell signals were heard was about 40 miles.

Thus within a few hours after leaving Hoboken, it was apparently demonstrated that navigation could be effectively safeguarded by the MV hydrophone, since by its aid the direction of submarine bell signals was accurately determined at ranges varying from 15 to 40 miles and the propeller sounds of near-by vessels heard and the vessels located thereby at ranges sufficient for avoiding collisions. With such information at his disposal, the navigator should be able to take his vessel into or out of port during fog or other conditions of low visibility.

The next day it was a matter of disappointment to find that the propeller sounds of the *Von Steuben* could not be heard in depths much greater than 500 fathoms. This result led to the important discovery that the MV hydrophone is able to give a reliable and continuous record of the depth of water beneath a vessel, steaming at any speed, up to depths of approximately three times the length of the vessel and that this record becomes more and more accurate as the depth of water becomes less.

Only Sound Reflected from the Sea-Bottom is Heard on Hydrophones Located Near the Surface.

The fact that propeller sounds of the *Von Steuben* could not be heard in deep water led at once to the conclusion that the hydrophone is affected only by sound that has been reflected from the sea-bottom. Two explanations of this fact are offered.

Referring to Fig. 1, sound from a source such as a propeller (S) reaches the hydrophone receiver (H) by three different paths, namely: $S—P—H$, $S—R—H$, and $S—O—H$ respectively. If the distance $S—H$ is great with respect to the distance $P—R$, that is, if the separation of source and receiver is great compared to their submersion below the surface, then the two paths $S—P—H$ and

S—R—H are nearly equal. The reflection at (*P*), being from a rare to a dense medium, introduces a change of phase of one half the wave-length and as a result the sound which travels directly

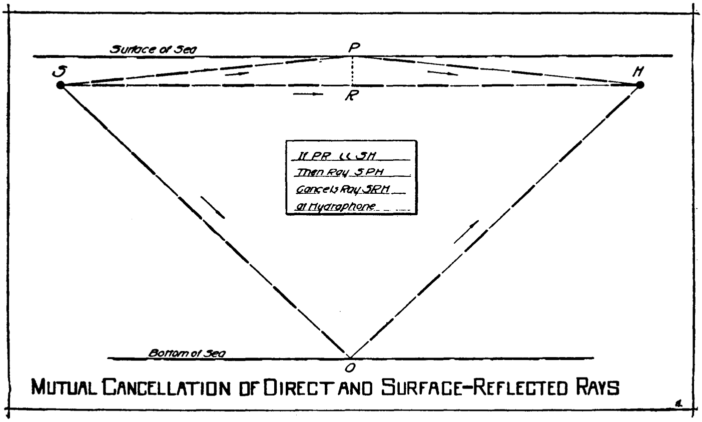


FIG. 1.

from (*S*) to (*H*) and that which is reflected from the surface will give almost complete interference at the receiver (*H*) and only the sound reflected from the bottom (*O*) will be heard.

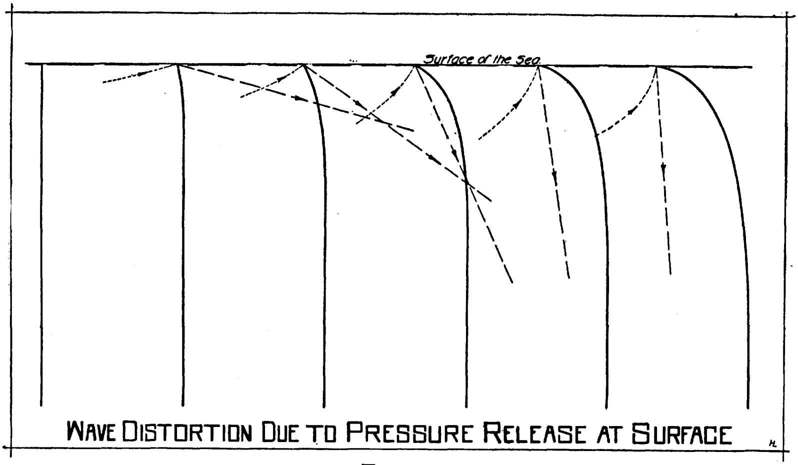


FIG. 2.

Referring to Fig. 2, the surface of the water represented by the horizontal line is a region of pressure release and as a result the rare

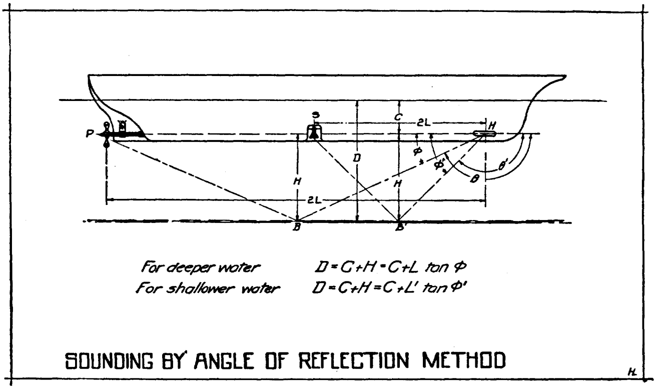
and dense portions of the sound waves will not remain perpendicular to this surface. If the sound travels from left to right the wave front will be distorted to the left as shown by the full curved lines. This distortion becomes greater as the sound travels farther from the source, and at considerable distance it is conceivable that all sound reaching the surface is travelling in a direction nearly perpendicular to it and thus will be reflected nearly vertically downward. If this distortion extends to a sufficient depth, neither the direct nor the surface-reflected sound ray will reach the distant receiver placed near the surface. Under such conditions only sound reflected from the sea-bottom will be heard.

Experiments for determining which of the above explanations is valid have not been undertaken to date. However, when listening to bell and oscillator signals, it has been noticed that the harmonics are more prominent relative to the fundamental at the first instant of response than during the rest of the signal. This fact tends to substantiate the first explanation. The slight difference in path length between the direct and surface-reflected sound introduces more phase difference between the high-pitched components of the sound than in the case of the fundamental and therefore the harmonics are less perfectly neutralized by interference at the receiver than is the fundamental. The sound at the receiver resulting from these two paths consists largely of harmonics and this is heard an instant before the sound which is reflected from the sea-bottom as the latter has travelled a somewhat longer path.

A New Method of Sounding.

Since the only propeller sound heard by a hydrophone located at a distance and near the surface is the component reflected from the sea-bottom, it follows that the depth of water can be determined from the angle which the reflected sound makes with a fixed line in a plane determined by the sound source and the reflected ray—provided the distance between the hydrophone and sound-source is known. Conversely, the distance between the hydrophone and the sound-source can be determined if the depth of water is known.

Referring to Fig. 3, let (H) represent the position of the MV hydrophone and (P) the ship's propeller. The sound heard by (H) has traversed the path P—B—H, making an angle ϕ with the surface. If $(2L)$ is the distance between the propeller and the hydro-



SOUNDING BY ANGLE OF REFLECTION METHOD

FIG. 3.

phone, both located a distance (C) below the surface, and if the sea-bottom is a horizontal plane, then the depth (D) is given by the equation

$$\begin{aligned} D &= C - L \tan \theta, \\ &= C + L \tan (\pi - \theta), \end{aligned}$$

or

$$D = C + L \tan \phi.$$

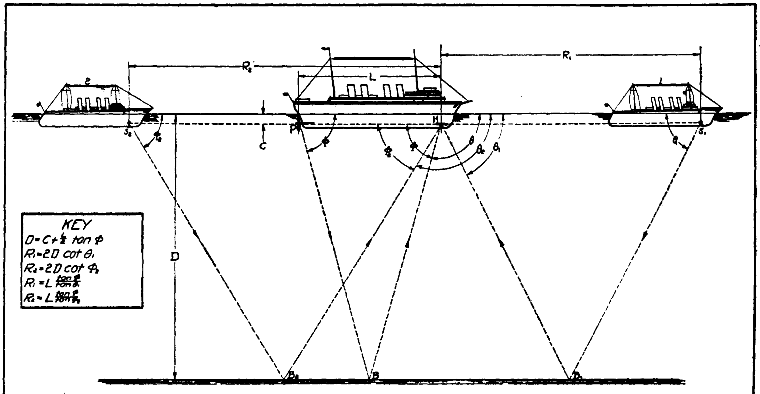
This equation will be referred to as the "sounding equation" and the angle ϕ will be referred to as the "sounding angle." It is to be noticed that the compensator scale is designed to feature θ, the angle the sound makes with the ship's keel extended forward, in order to give directly the relative bearing of surface vessels. The sounding angle ϕ is the supplement of this angle.

The range of a vessel ahead or astern can be determined roughly if the depth of water is known, since the hydrophone determines the angle which its reflected sound signals make with the surface.

Referring to Fig. 4, where S_1 or S_2 represents an artificial sound-source upon a vessel ahead or astern of the vessel equipped with the hydrophone (H), we have

$$R_1 = 2D \cot \theta_1,$$
$$R_2 = 2D \cot \phi_2,$$

the depth (D) being taken from the chart. It is to be noticed that for ranges ahead the compensator reading, θ, occurs in the equation while for ranges astern the "sounding angle," ϕ, is used.



METHOD OF SOUNDING AND RANGE FINDING BY M-V HYDROPHONE

FIG. 4.

If the depth is not too great, (D) can be determined by the hydrophone as outlined above and the range formulæ become

$$R_1 = L \frac{\operatorname{Tan} \Phi}{\operatorname{Tan} \theta_1},$$
$$R_2 = L \frac{\operatorname{Tan} \Phi}{\operatorname{Tan} \Phi_2},$$

where (R) is the range to be determined, (L) the distance between the sound-source and hydrophone on the listening vessel, and θ_1, θ_2, and Φ are the angles which the reflected sound from the three vessels make with the surface as shown.

It is evident that the range to which these formulæ will give reasonably accurate determinations is proportional to the depth of water in which the vessels are operating.

The equation connecting (D), the depth, and Φ, the angle which the reflected sound makes with the surface, becomes somewhat com-

plicated if the line of hydrophone receivers is not parallel with the surface and with the center-line of the vessel, or if the sea-bottom is not horizontal. This complication, however, consists largely in the addition of constant terms. Pitching of the vessel or variation of the sea-bottom from a horizontal plane causes the angle Φ to vary somewhat from the ideal conditions cited but, as will be shown later, such variations do not seriously interfere with the determination of depth.

Both Vertical and Horizontal Angles Determined by MV Hydrophone.

The MV hydrophone measures the angle included between a line passing through the receivers and an intersecting line defining the direction of the approaching sound. From conditions of symmetry the latter line can be rotated around the former without changing the required compensation. Otherwise stated, the same compensator setting will serve for sound traversing any element of the conical surface so generated. The angle of the cone is determined always by the compensator setting and if the line of receivers is parallel to the ship's keel in a vertical plane and to the water surface in a horizontal plane, the same compensator scale will serve for determining the direction with respect to the ships keel of sounds traversing either of these planes.

Errors Introduced by Pitch and Roll Readily Eliminated.

In general the hydrophone receivers are located along a line parallel with the ship's keel and at the same depth as the propellers. Under such conditions the compensator measures directly θ, the supplement of the sounding angle Φ—provided the vessel "rides on an even keel." Rolling of the vessel will not affect the determination of this angle but pitching will.

The angle of pitch for large vessels is very small except during unusually rough surface conditions and, except at such times, the error introduced by pitching of the vessel need not be considered. It has been found in practice that for large vessels the pitching motion is sufficiently slow to allow the operator to measure the sounding

angle while the vessel is in a horizontal position or to measure the angle at each end of the pitching motion. If the latter plan is pursued the average of the two angles gives the correct value.

Errors Introduced by Shelving Bottom Can be Eliminated.

A consideration of Fig. 5 shows that the errors introduced by shelving of the sea-bottom can be eliminated if a hydrophone and a sound-source are placed in both the bow and the stern of a vessel

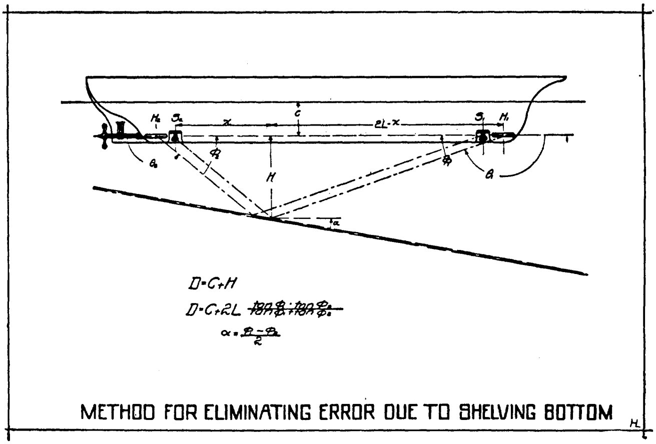


Fig. 5.

Let (S_1) and (H_1) represent a sound-source and hydrophone respectively, located near the bow of the vessel and (S_2) and (H_2) another sound-source and hydrophone located near the vessel's stern. Sound from (S_1) and (S_2) reflects from the same portion of the sea-bottom, making angles with the horizontal at (H_2) and (H_1) of Φ_2 and Φ_1 respectively.

If $(2L)$ is the horizontal distance between (S_1) and (H_2) and between (S_2) and (H_1), then

$$D = C + (2L - X) \cdot \tan \Phi_1,$$

and

$$D = C + X \tan \Phi_2.$$

Thence

$$D = C + 2L \frac{\tan \Phi_1 \cdot \tan \Phi_2}{\tan \Phi_1 + \tan \Phi_2}.$$

Moreover, the angle α which the sea-bottom makes with the keel of the vessel, assumed to be horizontal, is given by the relation

$$2\alpha = \Phi_2 - \Phi_1.$$

If $\Phi_1 = \Phi_2$, the formula reduces to the sounding equation, viz.:

$$D = C + L \tan \Phi.$$

In practice it has been found that shelving of the sea-bottom is seldom rapid enough to cause any great error in the determination of depth, especially for depths within 15 or 20 fathoms, and for purposes of navigation a single hydrophone located in the bow of the vessel and a sound-source located near the stern have been considered sufficient. Such an installation tends to err by giving too great depths when approaching shallow water and too small when approaching deep water. This error has been checked by taking soundings out and in on same course and found to be negligible in the most cases.

Soundings taken on a shelving bottom with any of the various types of sounding machines err in the some direction as do soundings given by the simple hydrophone installation described, if the sounding weight is launched from the stern of the vessel. Since the lead reaches bottom some distance behind the vessel, it will register too great depths when approaching shoal water and too small depths when entering deeper water. The hydrophone method has the advantage that the error is independent of the speed of the vessel while in case of the sounding machine the error increases with the speed.

Errors Introduced by Incorrect Determination of Sounding Angle.

The MV hydrophone determines direction by measuring the difference in time between reception of the sound by the two groups of receivers which connect with the two ears respectively; or, what amounts to the same thing, by determining the path difference between the sound-source and the two groups of receivers. This time difference or path difference is measured by introducing sufficient compensation into the paths connecting the receivers to the ears to

make the sound appear centered in the listener's head. It has been found in practice that the average listener can determine the path difference in water to within about one half inch.

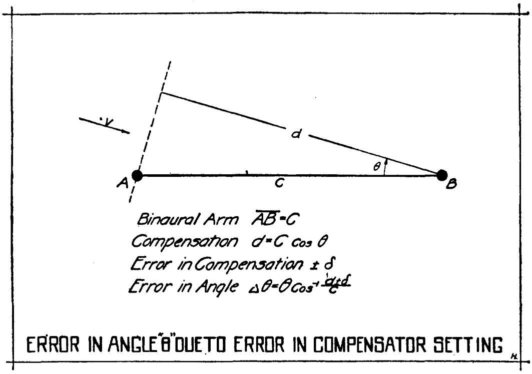


FIG. 6.

Referring to Fig. 6, it will be seen that this error due to the personal element may introduce a relatively large error in the determination of θ and hence the same error in the sounding angle Φ which is the supplement of θ.

For simplicity assume the hydrophone to consist of two single receivers (A) and (B), Fig. 6, one connecting with each ear and separated a fixed distance (C). Sound approaching from the direction represented by vector (V) makes an angle θ with the line joining the two receivers. The operator determines this angle by measuring the distance (d) to within one half inch. Calling this error δ we have the following relation

$$\theta = \cos^{-1} \frac{d - \delta}{C}.$$

The accuracy with which this equation determines θ is proportional to (C), the distance between the two receivers, and varies with the value of (d). Since the value of the cosine changes slowly with change of angle as the value of the angle approaches zero, it is evident that the value of δ will produce an abnormally large error in the determination of θ when the direction of the sound approaches parallelism with the line connecting the receivers. It is to be noticed that in determining the sounding angle Φ this condition is approached when the vessel enters shallow water.

The sounding equation, $D = C_1 + L \tan \Phi$, on the other hand, would seem to predict that the depth of water (D) is determined with greater accuracy as the water becomes more shallow, since the value of the tangent varies less rapidly with variation of the angle as the angle approaches zero. This does not hold true, however, for the reason that the error in the determination of Φ becomes abnormally large as the value of this angle approaches zero and it results from these considerations that depths of from 2 to 5 fathoms are not determined with as great accuracy as depths from 10 to 20 fathoms if hydrophones of the type described are used. This type is shown in the left-hand diagram of Fig. 7, where the line of the receivers is horizontal and parallel with the ship's keel.

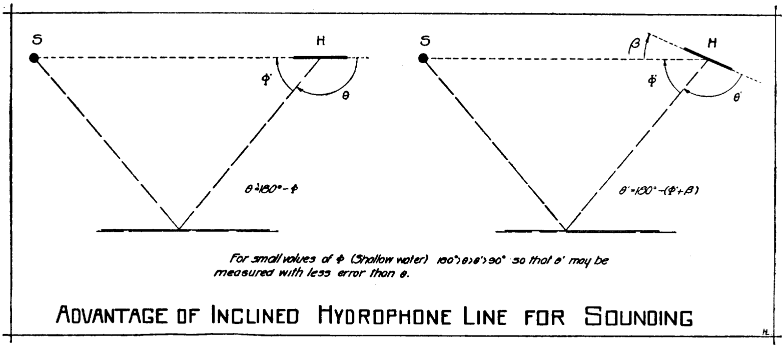


FIG. 7.

This weakness arises whenever the same hydrophone receivers are used for determining both the bearing of vessels or shore signals and also for taking soundings. It is readily removed if a separate set of receivers is installed for *sounding purposes only*. These receivers are mounted in a vertical plane parallel to the keel and along a line making an angle of about 30° with the surface, the forward end of the line of the receivers being lower as is shown in the right-hand diagram of Fig. 7. With such an arrangement of receivers the sounding angle Φ will be given by subtracting 30° plus the angle given by the compensator from 180°, and the compensator will only be required to determine angles between 60° and 150°. In this way the most accurate part of the compensator scale is utilized for deter-

mining depths and the determination then becomes progressively more accurate as the water becomes shallower.

The addition of a separate line of receivers does not complicate or materially increase the cost of the installation, since by means of a multiple-pole switch the same compensator can be used on all the receiver lines. The electrical compensator is provided with such a switch.

Another method of reducing the sounding error in shoal water, which is applicable to larger vessels, is as follows: If an artificial sound-source is placed near the center of the vessel, as shown at (S) in Fig. 3, it is evident that accurate shoal soundings can be taken without the addition of a line of receivers inclined to the horizontal. The reflected sound from this source does not approach parallelism with the line of receivers except for extremely shallow water. With such an arrangement an operator in taking deep soundings will make use of the stern sound-source (the propeller), while for soundings in shallow water he will utilize the centrally located sound-source.

It is evident, from a consideration of the sounding equation, that the error in the determination of the depth (D) resulting from the error in the determination of the sounding angle Φ will become abnormal when the depth is sufficiently great to cause this angle to approach $90°$, since the value of the tangent then varies rapidly with change of angle. This weakness can be partially overcome by separating the sound-source and the hydrophone as far as possible. When the hydrophone and the sound-source are placed in opposite ends of the vessel, reliable soundings are given for depths as great as three times the length of the vessel.

Graphical Representation of Errors Introduced by Incorrect Determination of Sounding Angle.

In order that the nature and magnitude of the errors in sounding, due to incorrect determination of the sounding angle Φ, may be more clearly understood, these determining factors will be illustrated graphically.

In Fig. 8, the full line in the center of the shaded area gives the relation between depth and sounding angle Φ when the sounding equation

$$D\ (\text{fathoms}) = 1 + 22.6 \tan \Phi\ .$$

is plotted. The constants (C) and (L) are given in fathoms and refer to the MV hydrophone installation on the U. S. S. *Bernadou.* The curve assumes that Φ is accurately determined.

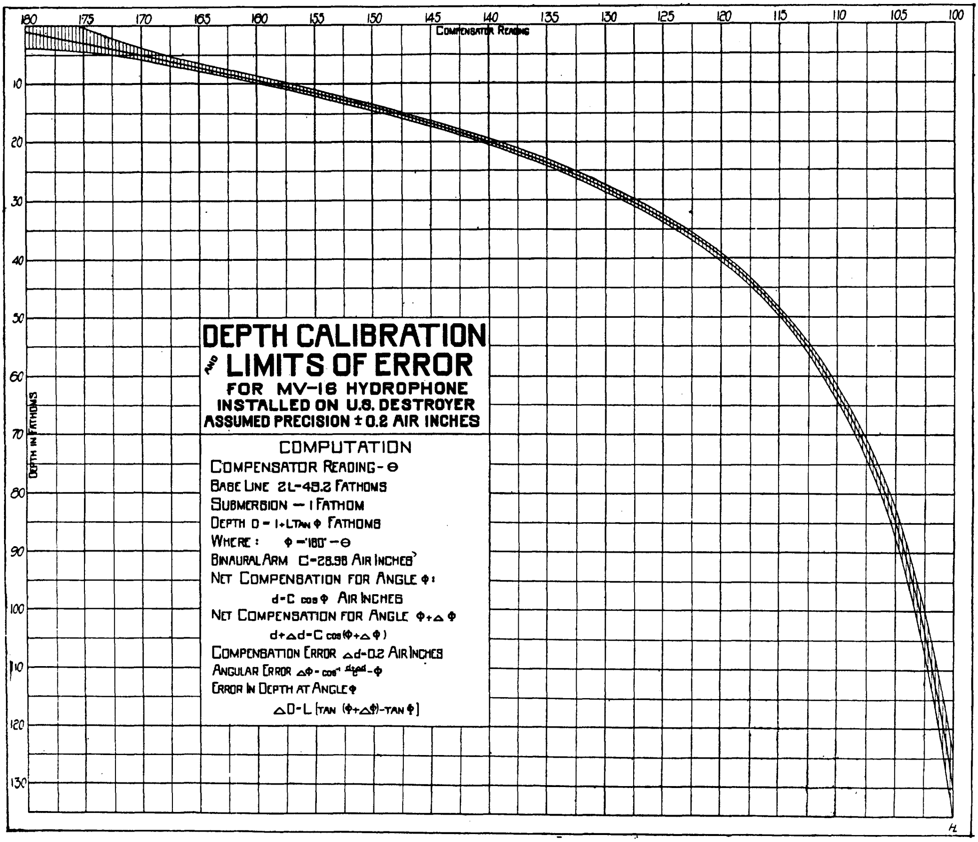


FIG. 8.

It has been shown, however, that $\Phi = (\pi - \theta)$ where

$$\theta = \cos^{-1} \frac{d \pm \delta}{C}.$$

If now we take for δ the value $\pm$ 0.2 inches of air path (which is equivalent to $\pm$ 0.87 inches of water path), this value being a conservative estimate of the precision of compensator setting, we may

ascertain the corresponding limits of error as a function of the depth by plotting the curves represented by the equation:

$$D \text{ (fathoms)} = 1 + 22.6 \tan \cos^{-1} \frac{d \pm 0.2}{28.98},$$

taking for the binaural arm (C) its value 28.98 inches in air (the water path is 126 inches) and for the variable (d) the net compensation of the line corresponding to various values of the sounding angle Φ.

These curves have been drawn, one on either side of the true sounding curve. Due to this personal error in determining Φ, the maximum limits of which are set as ± 0.2 air inches, it is evident that a given sounding is liable to fall anywhere within the shaded area bounded by these two curves. It is to be noticed that this area widens in a vertical direction at both ends of the curve, *i.e.*, the error for very shallow and for great depths is greater than for intermediate depths. The hydrophone installation in question has the receivers installed along a horizontal line parallel to the ship's keel, as shown in the left-hand diagram of Fig. 7.

In Fig. 9 the maximum error is plotted against depth as abscissæ and shows how the error is reduced for small depths when the line of receivers is inclined to the ship's keel. The full line curve shows the maximum error for various depths when the line of receivers is parallel to the center line of the ship. The error increases rapidly for depths below 10 fathoms. The broken line curve made of long dashes gives the maximum error when the line of receivers is inclined 30° to the horizontal in the manner shown in the right-hand diagram of Fig. 7. Here the error at great depths is not materially increased. The third curve gives the error when the line of receivers is inclined 60°. This arrangement further reduces the errors slightly in shallow depths but clearly at the expense of increasing it considerably at greater depths.

It has been found that best results are given when the line of receivers is inclined about 30° to the keel. Such an arrangement reduces the error in shallow water sufficiently for all practical purposes and at the same time does not materially increase the error for greater depths.

In practice the compensator is provided with a separate scale which is calibrated to give soundings in fathoms. To determine the depth of water the listener adjusts the compensator until the propeller sounds or submarine signal sounds off his own vessel are binaurally centered and then reads off the value directly from the

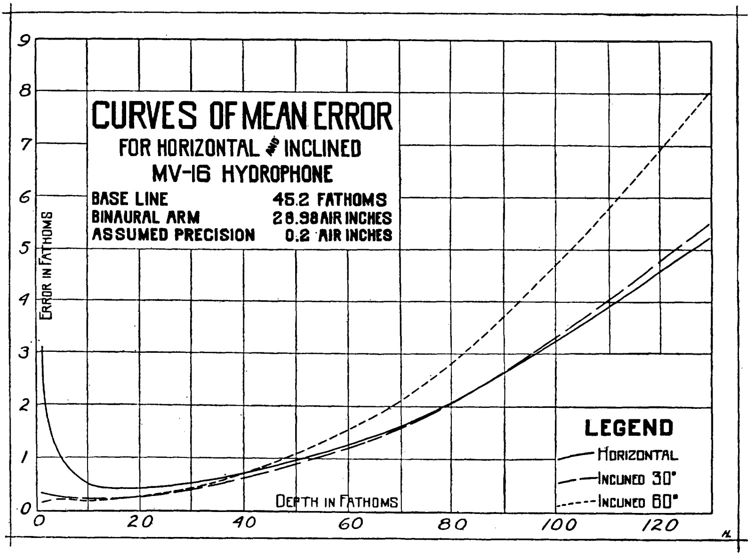


FIG. 9.

sounding scale. This operation takes but a few seconds, so that a continuous sounding record can be taken when desired and, as is shown, the record becomes more accurate as the water becomes shallower.

SOUNDING IN DEEP WATER.

The angle of reflection method only gives reliable soundings for depths less than three times the length of the vessel, but if the vessel is equipped with both an MV hydrophone and a proper submarine signal, an intermittent sounding record can be taken in water of any depth. Such soundings are determined by measuring the time required for a sound signal to travel to the bottom and reflect back again to the surface or, in other words, by measuring the time which elapses between the sounding of a signal and the response of its echo on the hydrophone.

This method of sounding, which is very simple in principle, is not new. It differs from the first method described in that it depends *upon the accurate measurement of a time interval* (a difficult operation in practice), whereas the new method depends *upon the measurement of an angle* (a comparatively easy operation). Moreover, the error in soundings due to incorrect determination of the time interval is as great for shallow as for deep water, whereas the error due to incorrect determination of the sounding angle becomes very small for shallow water.

The velocity of sound in sea water at the ordinary temperatures met in practice is roughly 4,400 feet per second. This velocity is so great that stop-watch methods are not sufficiently accurate for measuring the time intervals, since an error of one fifth second results in a discrepancy of over 70 fathoms in the determining of depth. The various laboratory methods of measuring time intervals with a high degree of accuracy require a skilled operator and in general can not be employed on board ships. Several devices designed for marine use in connection with this problem have been perfected but have all proven to be too complicated to be successfully operated by a ship's personnel.

The writer is at present developing a new method which looks very promising and by which the time interval between two signals can be determined with a high degree of accuracy on shipboard. The perfection of such a device will make possible the taking of soundings with a fair degree of accuracy in water of any depth while the vessel is steaming at full speed.

Determination of the Range of a Sound-Source.

If both a radio and an underwater sound signal are sent simultaneously from one point, the distance to the same can be determined by measuring the time interval which elapses between reception of the two signals at a distant point. In this way lightships or other points provided with underwater navigation signals can be accurately located. This procedure has been tried by stop-watch methods with mediocre success, but it is believed that the device mentioned above will make it possible to determine the range of a sound-source with

the same high degree of accuracy. This apparatus, which can not be described at this time, makes use of the MV hydrophone.

Locating Vessels in Deep Water.

The experimental results, obtained on the *Von Steuben*, led to a belief that MV hydrophones could not safeguard navigation in deep water by locating propeller sounds of other vessels. Believing that this weakness could be removed if ships were equipped with a proper type of submarine sound signalling device, a series of experiments were carried out in mid-ocean between the U. S. S. *Von Steuben* and the U. S. S. *Wilkes* the latter vessel, a destroyer, being equipped with a submarine oscillator. The tests were conducted in depths varying from 1,000 to 2,500 fathoms.

The oscillator signals were heard clearly to a range of 35 miles when the *Wilkes* was abeam and from 10 to 20 miles when ahead or astern of the *Von Steuben*.

The range (R) of the *Wilkes* (see Fig. 4) was determined several times while she was running ahead of the *Von Steuben* by measuring the angle θ_1 which her oscillator signals, reflected from the sea-bottom, made with the horizontal and using for (D) the charted depth which was rather indefinite through the region wherein the experiments were conducted. Nevertheless, these ranges agreed fairly well with values computed from time and speed data or with optical measurements.

Both theory and subsequent researches indicate that the oscillator on the *Wilkes* was not best suited for these experiments, but the tests demonstrated beyond a doubt that the hydrophone can safeguard navigation in any depth of water if all vessels are provided with an MV hydrophone and a submarine oscillator. Such an equipment will then give the bearing and course of every vessel within a radius of from 15 to 40 miles. Furthermore, the range of vessels approximately ahead or astern can be roughly determined if the depth of water is known.

It is quite probable that in the future all sea-going vessels will be equipped with hydrophone apparatus of the MV or other approved type, together with a suitable sound-source. Then maritime law will

doubtless require submarine code signals to be sent out at frequent intervals during conditions of low visibility. These signals will designate the code number or " call " of the ship, its compass course and possibly the speed which it is making. Other vessels in the vicinity on receiving these signals and on obtaining a hydrophone bearing upon them will have at their disposal much valuable information which will aid them in steering a clear course and avoiding disastrous collisions.

Such bearings will be far more trustworthy than those afforded by fog whistles now universally used, not only because of the greater ranges at which they may be obtained but also due to the fact that the sea is a relatively homogeneous and stationary medium which permits the definite linear propagation of sound. Every navigator knows the unreliable nature of fog whistles which are not only deadened by a counter wind, thus giving an erroneous idea of range, but which frequently suffer erratic and wholly indeterminate refractions and reflections as they encounter fog banks and cross-currents of air. As a result their propagation is far from linear so that false bearings of their source are obtained from which dangerous emergencies sometimes arise.

Locating Icebergs, Derelicts, etc.

Because of its focusing ability, the MV hydrophone can determine the direction of comparatively faint sounds while the vessel, upon which it is installed, is underway. If the sounds come directly from the source, it gives the bearing of the source; but if the sound has been reflected, it gives the bearing of the reflecting surface.

Direct tests for locating icebergs and derelicts by hydrophone have not been undertaken to date but indirect evidence obtained while conducting tests at New London, Connecticut, leads strongly to the belief that such obstructions can be located by hearing and determining the direction of submarine sounds reflected from their surface. The writer has often located the piers of the railroad bridge at New London, Connecticut, by the reflected propeller sounds of the listening vessel and has also been able to locate Valiant Rock, which lies in the passage between Fishers and Little Gull Islands, and in a like

manner the South-West Ledge at the entrance of New London harbor.

Since ice forms an excellent reflecting medium for submarine sounds, as does also the hollow hull of a vessel, it seems certain that high-pitched oscillator signals should reflect from such surfaces with sufficient intensity to be heard on the hydrophone. In practice the listener would focus the hydrophone dead ahead and send intermittent sound signals with the oscillator. If at any time the signal appears binaurally centered, the sound is then being reflected from a surface dead ahead and collision with the same may readily be avoided.

Several years ago attempts were made to locate icebergs by the echo method but failed for want of a device that could give the direction of the reflected sounds. The MV hydrophone supplies this want and with its aid it is believed that the experiments when repeated will prove successful and introduce a means of preventing such appalling disasters as befell the ill-fated *Titanic*.

Character of the Sea-Bottom—Hydrographic Surveys.

The hand lead and the sounding machine not only give the depth of water but also the character of the sea-bottom. The latter information oftentimes is as valuable as the former in locating the position of a vessel. The question, therefore, naturally arises, "Can the hydrophone give any information concerning the character of the sea-bottom?"

The answer to this question is "Yes." The character of the reflected propeller sounds varies with change in the character of the sea-bottom both as to intensity and to quality. These variations are so marked that a trained listener needs only to travel back and forth over the same course but a few times before he is able to recognize various regions en route by the character of the propeller sounds.

While experimenting in Long Island Sound the writer has often noticed a decided change in the intensity of the propeller sounds when the listening vessel was off Saybrook. This change is doubtless due to the fact that the sea-bottom in this region is covered

with sediment brought down by the Connecticut River. Other regions in the Sound were also easily recognized but thus far no attempts have been made to identify any particular sound characteristic with a particular kind of sea-bottom. Doubtless experiments along this line will prove interesting and valuable.

The hydrophone is destined to be of great aid in accurate, rapid, and detailed hydrographic surveys, affording as it does a continuous sounding curve over any desired course, at the same time giving an indication of the character of the bottom. For such researches a special design of hydrophone having an extended and variable base-line would probably be used. Thanks to the extensive labors of the hydrographic bureaus the coastal waters of this and several other nations are well surveyed, but the advent of the hydrophone into this field will facilitate the checking and extension of this information so vital to navigation.

The Hydrophone as an Auxiliary to the Radio.

Another field in which the hydrophone will doubtless serve as an aid to navigation is that of auxiliary to the radio. It has been clearly demonstrated that by the use of a proper sound-source and hydrophone, code messages may be exchanged up to ranges of from 15 to 20 miles by vessels under way, so that this equipment may be advantageously used for handling the "short traffic" communications between adjacent vessels or from vessel to shore. With the rapid growth and expansion of radio science the problem of interference becomes more vital every year so that the relief which may be afforded by hydrophone communication will, no doubt, be very welcome.

The use of powerful sound-sources, designed to be located off promontories, at harbor entrances, etc., and operated by power obtained from shore or installed upon light vessels will very materially increase the range at which such communication can be carried on or guiding bearings obtained, thus introducing the hydrophone into the field now occupied by the radio compass. One does not have to make many trips on the "trackless main" to appreciate the very positive value of each such additional source of information in situations of uncertainty and doubt.

On occasions when the radio is temporarily disabled, as for instance, when the antenna is carried away by a gale, the use of the hydrophone for communication purposes may be vital indeed.

The Hydrophone as an Accelerator of Commerce.

Doubtless, the most fruitful aspect from a financial point of view of the advent of the modern hydrophone is its use in speeding up commerce. When one considers the enormous loss in time and money which is occasioned by vessels being frequently obliged to lie idle when waiting for clear weather in order to enter or leave port or to otherwise navigate in restricted waters, it is at once evident that a device which will eliminate such delays needs little advertising. The aids thus afforded will soon cancel the expense of the installation and will subsequently pay high interest upon the investment.

The development of the art to date justifies the prediction that harbors and channels will be provided with suitable submarine sound beacons which will enable a vessel fitted with a hydrophone to safely navigate in such waters during thick weather.

Examples of the Use of the MV Hydrophone.

Having discussed some of the theoretical details of the MV hydrophone and having considered certain lines of its future development and application, it will now be of interest to relate a few actual experiences and results which have been obtained with various installations of this type of hydrophone upon certain ships of the U. S. Navy. These instances will serve to demonstrate the value of this device as an aid and safeguard to navigation.

U. S. S. Von Steuben.

Much use was made of the hydrophone installation on the *Von Steuben* during her several trips as a transport plying between New York and Brest. A particular instance will be cited.

Throughout one of her return trips cloudy weather was encountered, so that navigation was of necessity by "dead reckoning" methods without the aid of solar checks. Referring to the chart

given in Fig. 10, it will be seen that in the coastal waters south of New England the 100 fathom curve runs in a nearly east and west direction. It should also be noted that the shoaling inside of this

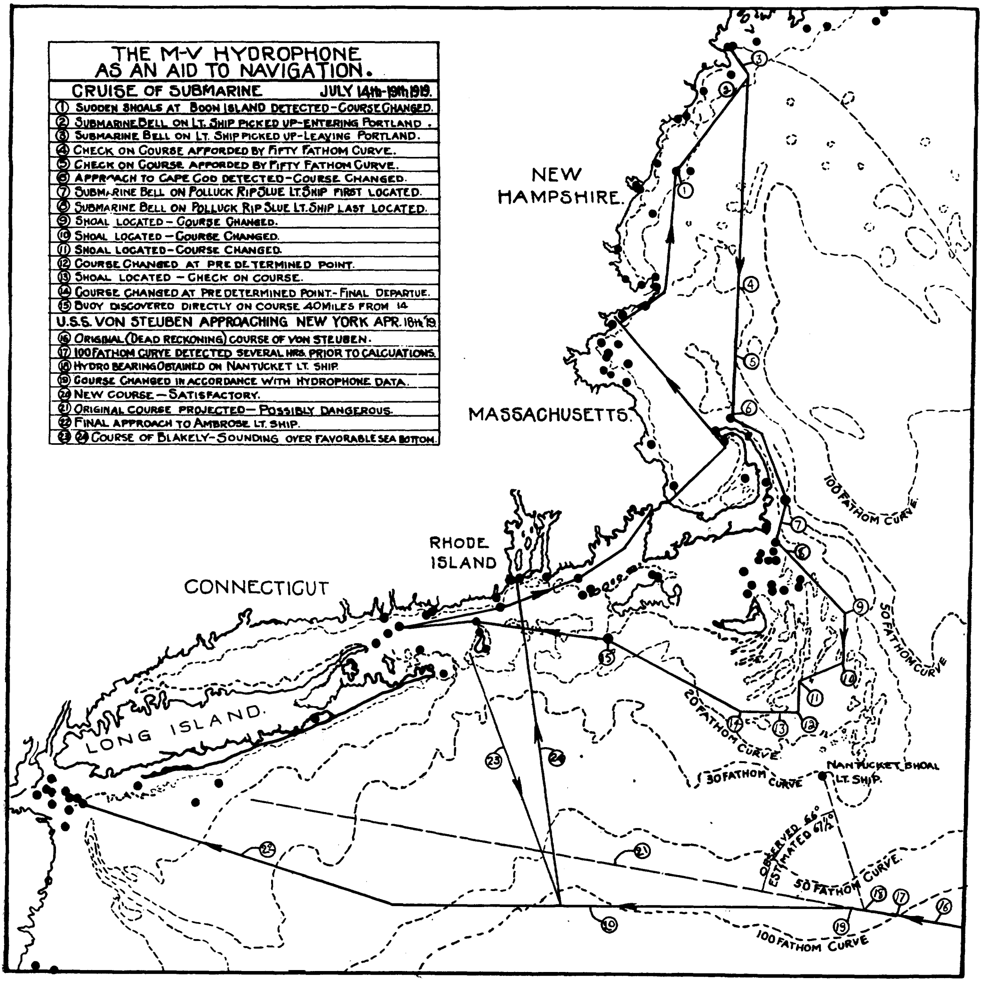


FIG. 10.

curve is comparatively slow, while outside of it the depth increases rapidly. This ocean plateau, which is crossed by all vessels entering or leaving New York for European or Mediterranean ports, is read-

ily detected by hydrophone soundings as a ship crosses it steaming at full speed. Computations had predicted that the *Von Steuben* would cross this 100 fathom curve in the vicinity of longitude 70:00 about 2 o'clock on a certain afternoon. It so happened that the *Von Steuben* was actually proceeding on a course indicated by (16) about 10 miles to the northward of the supposed position, so that she would accordingly arrive at this depth some little time prior to expectations.

The hydrophone operator, who was listening upon the apparatus during the morning, first heard faint sounds from his own ship's propeller, in a depth of about 450 fathoms, at 9:25 A.M. A rapid shoaling was subsequently observed and the 100 fathom curve detected at 9:45, position (17). At 10:15 the hydrophone gave the depth as 55 fathoms, which observation was checked by the hand-lead. At the same time, position (18), the submarine bell on the Nantucket lightship, distant 37 nautical miles, was heard and a relative bearing of 66 degrees obtained. Subsequent computations gave the value of 67.5 degrees, a close check. This hydrophone bearing together with the sounding data gave a satisfactory "fix" by virtue of which the course of the vessel was changed at (19) and a more satisfactory approach to Ambrose Channel made as shown (20) and (22).

It is worth noting that the original course of the *Von Steuben* projected (21) would have carried that vessel towards the Fire Island Shoals, where many unfortunate vessels have gone aground.

The Submarine Installation.

A submarine was equipped with electrical MV hydrophone lines and the writer participated in a test cruise on this vessel from New London, Connecticut, to Portland, Maine, and return, for the purpose of ascertaining the characteristics of this, the first MV installation of its kind to be made on a submarine. The course of the cruise is drawn upon the chart given in Fig. 10. The entire trip was made by surface running on the Diesel engines, the most unfavorable condition for long range listening. Prior to departure a sounding scale had been computed for the compensator in terms of

the base-line ($2L$) of the vessel. Accurate hydrophone soundings could be made at all times and these, as will be shown, were a very great aid in navigating.

During the first day's run from New London to Provincetown through the Cape Cod Canal, the weather was clear so that a close check upon the progress of the vessel could be kept by observation of beacons along the shore. Hydrophone soundings were made from time to time and these were seen to agree closely with the depths given on the chart, thus affording a check upon the computed scale. The same procedure was carried out during the second day when the trip was made across Massachusetts Bay to the port of Salem.

Departure from Salem was made in a heavy fog. After clearing Cape Anne a compass course was set for Boon Island, off the coast of York, Maine. This small island is rather peculiar hydrographically in that it consists of a small peak rising abruptly in a sea of fairly deep water. A continuous sounding watch was maintained until the hydrophone suddenly showed a very rapid shoaling of the water in the position marked (1). Warning was given just in time to enable the navigator to make out a buoy off the island which was passed at close range. Had it not been for these hydrophone soundings the locating of this small island would have been a more tedious and hazardous project in the thick weather prevailing. A course was then set for the Portland lightship; soundings were taken en route to check the progress of the submarine. The submarine bell on this lightship was picked up and located at position (2), something over a mile before reaching it. Further aid was also afforded by the hydrophone while passing Cape Elizabeth and entering the harbor.

The submarine left Portland two days later in a settled spell of thick weather. Taking a departure from the lightship a course was laid almost wholly by compass and hydrophone soundings. At many points along this route, such as are indicated by (4) and (5), sudden changes in the depth of water were very readily noted and afforded excellent checks upon the progress being made by the vessel—in this manner serving the purpose of the log. The shoaling water off the

tip of the cape was detected at position (6). The course around the cape was then easily followed until the submarine bell on the Polluck Rip Slue lightship was picked up at position (7), range 4 miles, and contact made with it.

Darkness had now fallen and with it an extremely heavy fog, so thick that the bow of the submarine could hardly be seen from the conning tower. It would, without doubt, have been possible to navigate the vessel through Nantucket and Vineyard Sounds, as was originally planned, with no great difficulty—as sounding and lightship bells would have given sufficient aid. However, it was thought that numbers of silent fishing boats might be anchored in these waters, offering a risk of collision. Accordingly it was decided to go out around these islands. The numerous and extensive shoals to the south of Nantucket are well charted so that a course was laid out beforehand with certain turning and checking points at various well-defined shoals—(9), (10), (11), (12), (13), and (14).

Taking a departure from the Slue lightship, which was the last beacon to be seen during the night, this predetermined course was readily followed. Hydrophone soundings proved to be thoroughly reliable; the various points indicated were located with ease, *so that the navigator, cruising at full speed through the fog and darkness, was certain of his position at all times and proceeded with complete confidence.* When the last shoal, (14), was reached in the early morning the hydrophone watch was interrupted and a compass course was set for (15), a buoy off No Man's Land, nearly 40 miles distant. About 9:00 A.M. the fog suddenly lifted; the island of No Man's Land was seen on the starboard bow, and a few hundred yards ahead was the buoy in question—less than a point off the course.

While this precise locating of the buoy after such a lengthy run from the Slue lightship out around the islands was perhaps to be partially attributed to the element of luck, nevertheless, all on board considered that this result showed conclusively the aid to navigation which a hydrophone equipment of this type is capable of furnishing, due to its ability to give reliable soundings while the vessel continues undelayed on her course. The trip, in spite of—or perhaps because of—the bad weather, was voted a complete success.

U. S. S. Blakeley.

The U. S. Destroyer *Blakeley* is equipped with an "acoustic-blister" type of MV hydrophone which has been used continuously for navigational purposes during the past year and has proved to be very reliable and advantageous. Two instances will be cited:

In June, 1919, the *Blakeley* was ordered to leave Philadelphia and to rendezvous with four other destroyers five miles south of Nantucket lightship. Upon clearing the Delaware Capes a heavy fog was encountered which held during the entire run to the Nantucket lightship. Difficulty was encountered in attempting to obtain "fixes" by means of radio compass bearings from shore stations, but at a distance of 12 miles the Nantucket lightship submarine bell was located and, by virtue of hydrophone bearings taken on this bell, an accurate position 3 miles south of the lightship was reached and a departure made for the Azores without sighting the lightship. During the fog and while in the vicinity of Nantucket, the propeller sounds of another vessel were picked up by the hydrophone at a bearing dead ahead. The course of the *Blakeley* was changed and the shift in bearing of the other vessel, which was not sighted, was followed until the assurance was given that she was well clear.

While en route from Pensacola to New York the *Blakeley* passed Hatteras during a certain forenoon in December, 1919, and laid a course to make a landfall on Barnegat Light. Before reaching this light, however, the vessel ran into a heavy fog and nothing was sighted until the Ambrose lightship was picked up about 8:00 A.M. the following morning. From the time the fog was first encountered the position of the *Blakeley* was checked by constant hydrophone soundings. A definite "fix" for latitude was obtained in crossing the deep water gulley off the entrance to New York harbor and the submarine bell of Ambrose lightship was picked up at a distance of about 7 miles, whence the ship's course was laid from bearings obtained on the hydrophone until the lightship was brought within sighting distance close abeam. The hydrophone could be relied upon to give warning of the approach of steamers from ahead and 15 knots speed was therefore maintained through the fog.

U. S. S. Breckinridge, Sounding Data Over Jagged, Uneven Sea-Bottom.

During the month of January, 1920, while making a trip from Charleston to Key West on board the U. S. Destroyer *Breckinridge,* the writer had an opportunity of testing the utility of the MV hydrophone for sounding purposes under very adverse conditions. The *Breckinridge* had been fitted with an electrical MV hydrophone, the lines of which were installed in tanks built in the bottom of the vessel near the bow. The tests were made over a period of 10 hours while the *Breckinridge* was proceeding down the coast on a course which ran in part along the edge of the continental shelf, so that the bottom was very uneven and erratic, and pronounced changes in depth occurred. Two successive casts of the hand-lead, made not more than one minute apart and taken with the vessel moving less than five knots, frequently showed a discrepancy of from 5 to 6 fathoms.

Time.	Chart Soundings.	Hand Lead.	Sounding Machine.	Hydrophone.	Position.	
					Latitude.	Longitude.
0900	12	—	14	14	32–20 N.	79–48 W.
0930	17	17¼	10	16	32–07	79–51
1000	19	21	20	20	31–55	79–54
1030	21	—	65	21	31–30	79–56
1100	24	30	35	21	31–30	79–59
1130	25	31	30	31	31–17	80–02
1200	26	31	30	27	31–05	80–05
1230	25	27	25	25	30–54	80–07
1300	25	31	26	26	30–44	80–09
1330	30	—	34 ?	29	30–33	80–11
1400	25–100	45	42	37	30–22	80–13
1430	25–50	46	46	46	30–11	80–15
1500	30	44	55	30	30–00	80–17
1530	26	32	38	22	29–49	80–19
1600	22	32	30	26	29–38	80–21
1630	17–23	28	23	21	29–28	80–23
1700	18	25	21½	18	29–16	80–25
1730	14	20	19	18	29–05	80–27
1800	11–12	17	13	13	28–54	80–29
1830	12	12¾	12½	13	28–44	80–27

At half-hour intervals soundings were made both by hand-lead and the automatic sounding machine, the vessel of necessity being slowed to about 3 knots for these operations. Just before stopping and after starting the propellers soundings were taken upon the

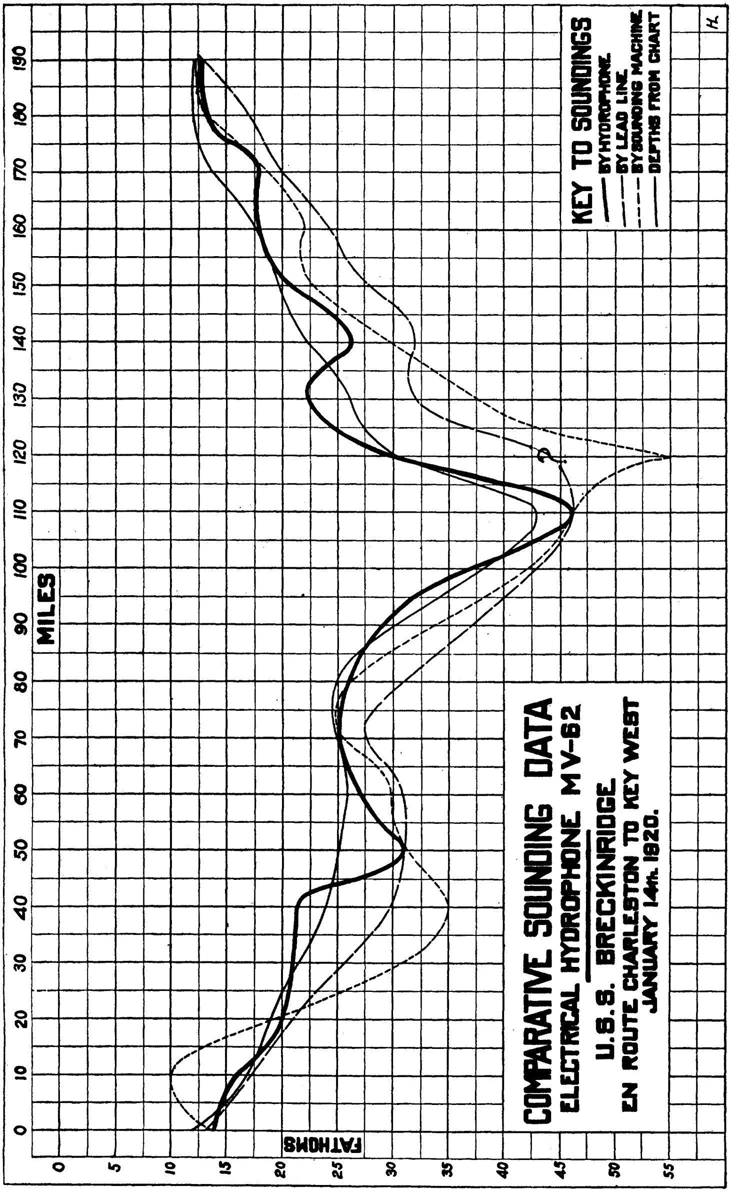

COMPARATIVE SOUNDING DATA
ELECTRICAL HYDROPHONE MV-62
U.S.S. BRECKINRIDGE
EN ROUTE CHARLESTON TO KEY WEST
JANUARY 14th. 1920.
KEY TO SOUNDINGS
BY HYDROPHONE.
BY LEAD LINE.
BY SOUNDING MACHINE
DEPTHS FROM CHART
MILES
FATHOMS
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190
0 5 10 15 20 25 30 35 40 45 50 55
H.

FIG. 11.

hydrophone in the usual manner. The depth was also noted as accurately as possible from the chart. These data are given below.

In order to show more clearly the variation between these different methods of sounding, the data have been plotted in Fig. 11 where the abscissæ represent distance travelled along the course and the ordinates the depth of water. Each of the four curves is a "sounding curve" taken by one of the four different methods as indicated in the key. These curves illustrate several interesting facts. In the first place, in spite of the discrepancies between the various values evident at certain places, it will be seen that, when two or more of the other methods do agree we find that the hydro phone sounding coincides with this point also. It should further be noted that the discrepancy between the hand-lead and the automatic sounding machine is, in general, quite as great as that between one or the other of these instruments and the hydrophone. Again, it is important to note that over the whole course the hydrophone soundng curve agrees most closely with the sounding curve taken from the chart. This fact shows that the hydrophone has a tendency to smooth out the local irregularities of an uneven bottom and to give an integrated mean curve which checks well with that obtained from the hydrographic charts. The depths given on the charts were obtained by taking an average of a number of soundings made in a given locality, thus canceling the local variations which are very prominent in this region. An illustration of this is to be seen on the 120-mile ordinate of the plot where the hydrophone and chart soundings agree, while the sounding machine evidently fell into a ravine, the bottom of which never was reached by the hand-lead. The greatest discrepancy (12 fathoms) between hydrophone and chart which occurred at 50 miles and whereat the sounding machine and lead checked the hydrophone evidently indicates a depression which was not noted on the chart.

The U. S. Blakeley, Sounding Data Over Favorable Sea-Bottom.

The curves in Fig. 12, plotted from data taken on board the U. S. S. *Blakeley* during a run from Block Island out to the 100

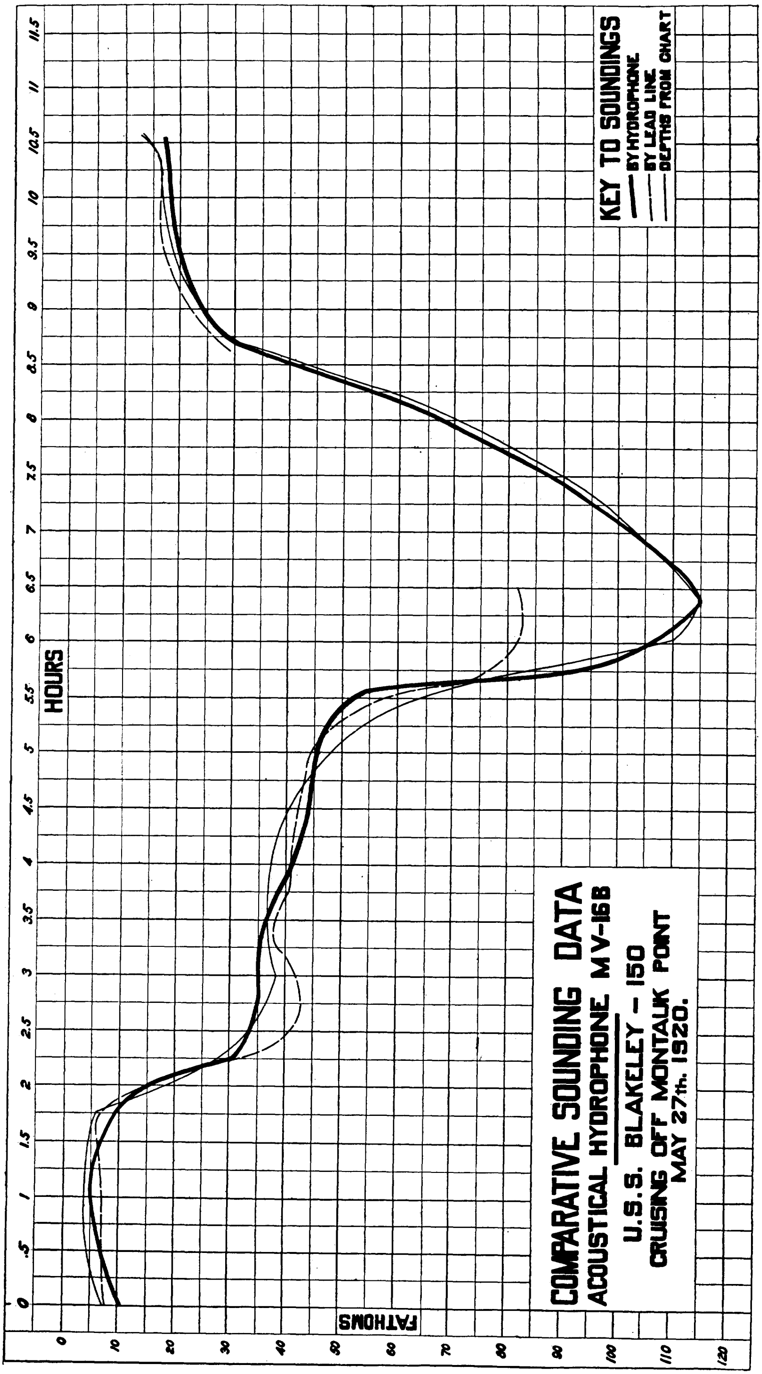

COMPARATIVE SOUNDING DATA
ACOUSTICAL HYDROPHONE MV-16B
U.S.S. BLAKELEY – 150
CRUISING OFF MONTAUK POINT
MAY 27th. 1920.
KEY TO SOUNDINGS
BY HYDROPHONE
BY LEAD LINE
DEPTHS FROM CHART
HOURS
FATHOMS
0 .5 1 1.5 2 2.5 3 3.5 4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9 9.5 10 10.5 11 11.5
0 10 20 30 40 50 60 70 80 90 100 110 120

FIG. 12.

fathom curve and back again into Newport Harbor, give some idea of the accuracy with which the MV hydrophone gives soundings over a favorable sea-bottom. (This course is laid off on the chart of Fig. 10.) Unfortunately the sounding machine broke down at the start, so the comparison data is not as complete as that taken on board the *Breckinridge*. The deep sea lead, however, was provided with a sounding tube which operated on the Kelvin principle and for depths beyond 10 fathoms the soundings were taken from this tube and not from the amount of line let out.

It is to be noticed that the hydrophone sounding curve (represented by the heavy full line) agrees very closely with the curve representing charted depths (light full line) except for the shoal area near Block Island. Here, however, the agreement with the soundings taken by the hand lead is almost perfect. The hand lead soundings in this region were taken with great care and there is no doubt in the minds of the experimenters but that the charted depths are about 2 fathoms too small.

The sounding tube seemed to function badly for depths beyond 50 or 60 fathoms and indicated little or no change for depths beyond 80 fathoms. At first it was suspected that the charted values were in error at the greater depths but the fact that the hydrophone soundings agreed closely with the charted depths and that the supposed position of the *Blakeley* checked perfectly on the return trip led all concerned to the belief that the charted depths are correct and that, on the whole, the soundings taken by the hydrophone are more reliable than those given by either the sounding tube or the chart.

Conclusion.

The MV hydrophone is the result of two years of intensive research work carried out by the Navy. It was developed as an instrument of warfare at a considerable cost and those best qualified to make such estimates claim that this expenditure is but a small per cent. of the saving to the Allied Powers which the hydrophone affected during the period of the war.

During the past year the Navy has discovered that the same qualities that enabled the MV hydrophone to detect and accurately

determine the direction of a submerged submarine enables it to serve as a powerful aid in safeguarding navigation in times of peace, and it is the confident belief of those most familiar with its operation that this device is destined to save more vessels and lives than were destroyed during the war by the U-boats that brought about its development.

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